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Sediment budget analysis: practitioner guide

Report: SC150011

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

A sediment budget summarises the balance of inputs and outputs for a defined system (such as an estuary or coastal embayment) and period of time.

The Coastal Research Development and Dissemination (CoRDDi) framework identified the need to provide further understanding of sediment budgets to improve decision-making in shoreline management planning. Sediment budgets are of central importance when managing the coast. For example, they are often developed to help determine whether specific policies or coastal defence options will increase, decrease or stop sediment movement from particular sources to particular areas.

The compilation of a sediment budget brings together a variety of data types for the different elements of the budget such as volumes of beach erosion or rates of longshore sediment transport. Some of these data can be drawn directly from monitoring surveys, while other data may require some form of analysis or deduction (including numerical modelling). This helps determine if that system has an overall surplus (accretion) or deficit (erosion) of material and therefore whether parts of a system are in balance/equilibrium. From this information, it is possible to understand how the system and features within it (for example, a beach, spit or bar) may respond to forcing mechanisms such changes to the wave regime.

This guide, designed for coastal managers, covers the breadth of coastal sediment budgets. These range from relatively simple shingle beach budgets (with well-known and quantifiable movements of material between 2 points along a coast) to complex estuarine budgets (with fluvial and marine inputs, different types of sediment and over larger spatial scales) and coastal systems with large offshore/onshore exchanges that can be even more difficult to quantify.

These budgets are useful in coastal management, especially when there is a need to gain a quick and relatively inexpensive characterisation and quantification of sediment transport. They also have value in shoreline planning, such as helping to communicate the wider benefits of existing or planned changes to management policies.

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1 Introduction

1.1 Why is this guide needed?

The Coastal Research Development and Dissemination (CoRDDi) framework identified the need to provide further understanding of sediment budgets to improve decision-making in shoreline management planning.

A sediment budget summarises the balance of inputs and outputs for a defined system (such as an estuary or coastal embayment) and time period. This helps determine if that system has an overall surplus (accretion) or deficit (erosion) of material, and therefore whether parts of a system are in balance/equilibrium. This information helps inform how the system and features within it (for example, a beach, spit or bar) may respond to forcing mechanisms such as a change in longshore sediment transport arising from a modification to the wave regime.

Sediment budgets are of central importance when managing the coast. They are often developed to help determine whether specific policies or coastal defence options will cause bypassing, interruption, reduction or cessation of sediment movement from particular sources to particular areas. Examples of where sediment budgets can support the Shoreline Management Plan (SMP) process include to:

- help to understand and communicate the wider benefits of allowing sediment loss in 'no active intervention' areas, considering sediment as 'natural capital'
- help to understand the options for adjusting policy and management options (for example, the innovative subtidal nourishments trialled in Poole Harbour or the super-nourishment planned at Bacton in Norfolk) to achieve the same broad outcome (for example, to 'hold the line')
- help to understand how and where best to use won material (for example, from dredging) and other external inputs to a sediment system to best effect to achieve a management goal
- help to understand the likely evolution of coastal realignments and intertidal habitat development generally, so that:
    - the compliance of SMPs with the ecological status requirements in the nature directives and the Water Framework Directive is maintained
    - realignment can be better targeted at areas that will work with the 'equilibrium' which a coastal/estuarine area wants to reach

The concept of sediment budgets will become increasingly important as we seek to understand coastal evolution, through ongoing human intervention and natural system adaptation to climate change. For example, it is known that many estuaries are continuing to infill with sediment and are currently able to keep pace with sea level rise. However, an understanding of sediment budgets is required to help determine whether this process will continue into the future as sea level rise continues over the longer term.

Sediment budgets are often developed in isolation, using a variety of supporting methods. These depend on many factors including:

- resource/ budget availability
- the data available

- sediment type
- geographic scale
- level of detail and accuracy required from the results

There is no consistent approach to the development of a sediment budget – often referred to as sediment budget analysis (SBA) – and the presentation of results, despite this being central to understanding coastal processes. Consistency in the execution of SBA can help the ‘transparency’ of decision-making, giving stakeholders consistency in the supporting evidence.

1.2 About this guide

This guide covers the whole breadth of coastal sediment budgets. These range from relatively simple shingle beach budgets (with well-known and quantifiable movements of material between 2 points along a coast) to estuarine budgets (with fluvial and marine inputs, larger spatial scales and more difficult to quantify sediment movements) to coastal systems (with large along and offshore/onshore exchanges that are even more difficult to quantify, like the UK East Coast).

The primary aim of this document is to support flood and coastal erosion risk management practitioners by providing a guide on the need and best practice on SBA. However, the guide also has wider applicability to other coastal practitioners including coastal managers and marine developers. The guide should also help enable consistent and comparable assessment of sediment budgets determined from around the UK.

The project has been developed through discussions within the Coastal Research and Development Steering Group. It has been subject to refinement through consultations with the Technical Advisory Groups.

This work has been supported by a Project Board with representatives from Defra, the Environment Agency and Natural Resources Wales, along with the Coastal Research and Development Steering Group as a wider sounding board for the work.

The acronyms and terms used in this guidance document to describe the concepts associated with a sediment budget are defined in the List of abbreviation and Glossary at the end of the report.

1.3 Who should use the guide?

This guide is appropriate to all organisations that have a strategic role in managing the UK coast. It provides guidance to help understand and interpret reports on sediment budgets.

The end users are therefore commissioning bodies involved in coastal management or marine development, consultancies undertaking the work, or regulators who need to comment on the specification and review the outcomes. The guide will also be useful when advising developers on the nature and scope of SBA for development purposes.

This guide draws on case studies from around the UK, along with practical experience in the development of sediment budgets by the authors. The intention is to augment existing guidance rather than supersede what is already available. This includes relevant contributions in the online Estuary Guide created for the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency in 2007

(ABPmer and HR Wallingford, 2007), which provides details regarding the use of SBA.[1] Another important source of information is the US Army Corps of Engineers Coastal Engineering Technical Note CETN-IV-15 (Rosati and Kraus 1999). A bibliography of supporting information is provided at the end of this report.

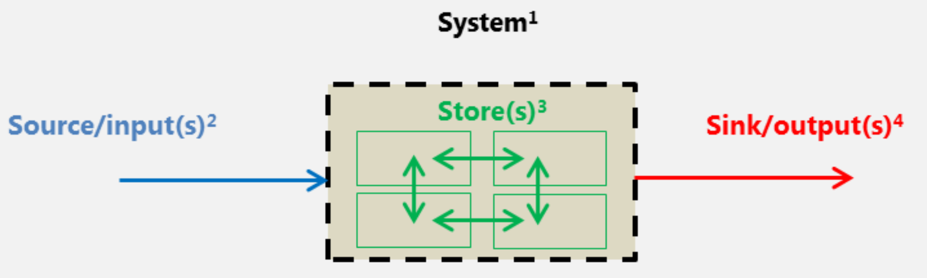
The guide sets out the appropriate use of SBA as a technique and is structured around the following topics:

- what is a sediment budget (see Section 2)
- when should sediment budget analysis be used (see Section 3)
- how to apply sediment budget analysis (see Section 4)
- using data to solve the sediment budget equation (see Section 5)
- managing uncertainty (see Section 6)

[1] The Estuary Guide provides a website-based overview of how to identify and predict morphological change within estuaries.

2 What is a sediment budget?

In the most basic form a sediment budget quantifies the balance of inputs and outputs for a defined length of coastline or system and period. This helps determine if that system has a net surplus or net deficit of material, and therefore whether it is in balance/equilibrium. This information then informs how the system and features within the system may respond. Figure 2.1 illustrates a simplified arrangement for a sediment budget, with examples provided in Box 1 for the section of coast between Selsey Bill and Brighton Marina and Box 2 for Southampton Water.



*1 **'System'** – the macro unit which contains all the functioning elements and sub-systems to explain the behaviour of an area of coast and which can be schematically represented in a system diagram.*

- Estuary
- Coastal 'cell' - (a bounded unit of coast within which the sediment is largely self-contained. Interruptions to the movement of sand and shingle within one littoral cell should not affect beaches in a neighbouring sediment cell)
- Combination of estuary(s) and coastal cell(s)

*2 **'Source'** – a location which contributes sediment into a system.*

- e.g. Cliff erosion
- e.g. Riverine sediment
- e.g. Beach recharge

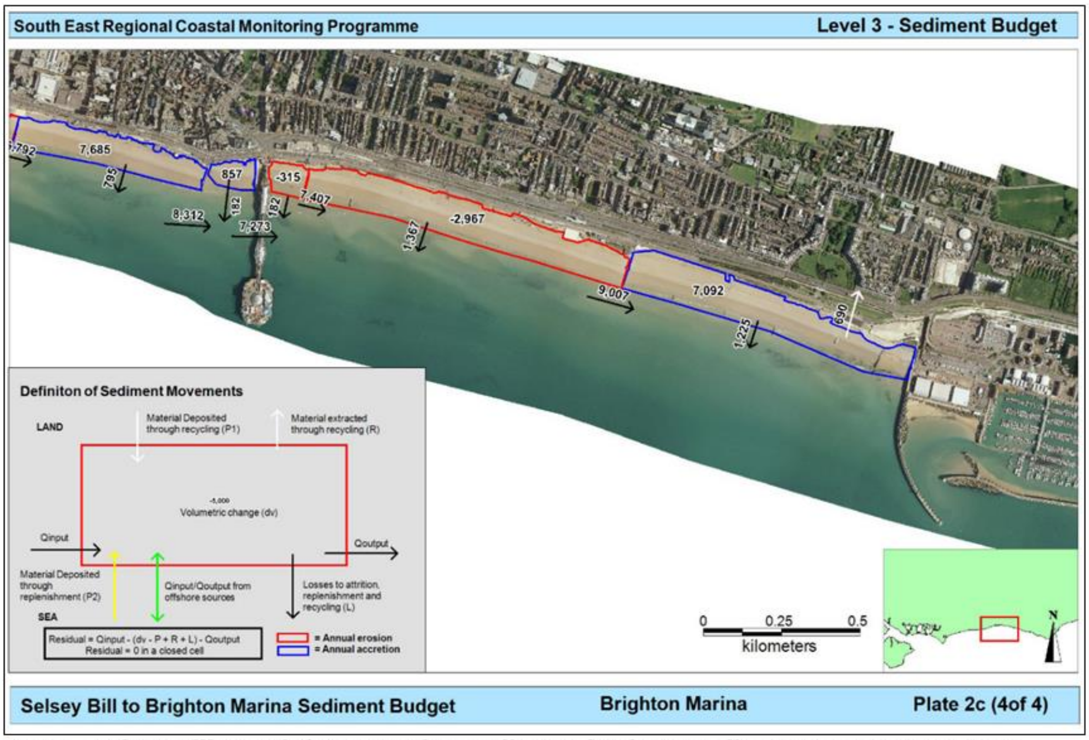
*3 **'Store'** – a location that may be able to receive and temporarily hold onto sediment, but may also subsequently contribute sediment back to the system under certain circumstances.*

- e.g. Beach,
- e.g. Fore-dune,
- e.g. Salt marsh
- e.g. Mudflat
- e.g. Spit
- e.g. Sand bank
- e.g. Sand bar
- e.g. Water column

*4 **'Sink'** – a location which permanently removes sediment from a system*

- e.g. windblown sediment transport
- e.g. accretional areas

Figure 2.1 Basic system diagram for a sediment budget with associated typology

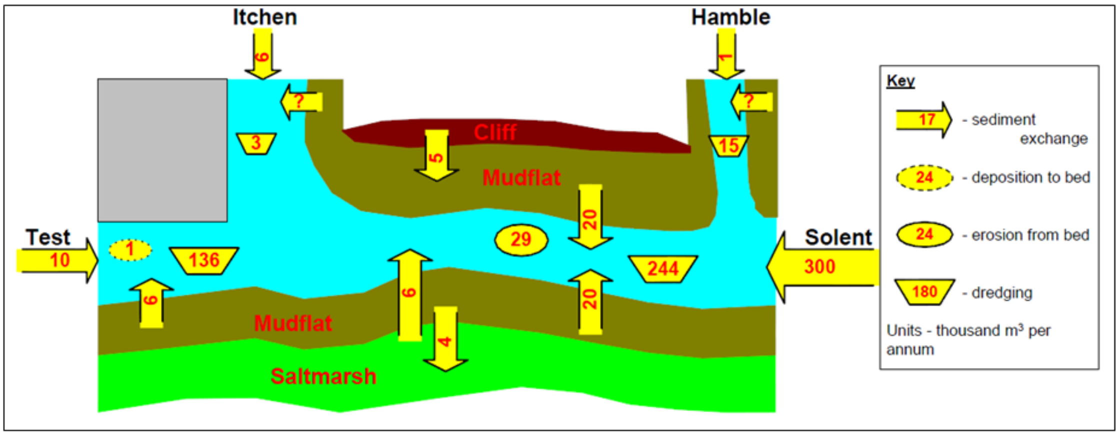


Box 1 Selsey Bill to Brighton Marina sediment budget: sediment movements near Brighton Marina (EKEP, 2013)

A shingle sediment budget for the coastal cells between Seasalter (North Kent) and Selsey Bill (West Sussex) was generated by the East Kent Engineering Partnership and Canterbury City Council to gain an understanding of sediment movements through the frontage. The sediment budget enables transparent and quantitative evidence of beach losses, gains and sediment pathways, in combination with both natural and artificial movements of beach grade material. The data used for the investigations was sourced from the Strategic Regional Coastal Monitoring Programme (SRCMP) with outputs from the SBA used to inform Beach Management Plans (BMP). The analysis was undertaken over a range of spatial scales with the local analysis taken forward to the regional scale to gain a greater insight into beach behaviour over interconnected sediment sub-cells.

SBA represents a quantification of the ‘conceptual understanding’ of sediment movements in a system. Conceptual understanding of a system describes how the processes of a system link together and evolve in response to applied forces.

The conceptual understanding is the first step to undertaking SBA. A sediment budget improves the conceptual understanding by quantifying the sediment transport as in Box 2. Outputs from numerical models (waves, tides and sediment transport) can be used to support the development and quantification of the conceptual understanding. However, it is important that such numerical modelling should not be seen as a substitute for conceptual understanding or SBA, but rather as a supporting tool.



Box 2 Schematic of the sediment budget for Southampton Water and tributaries – volumes x 10^3 m^3 /year (ABPmer and HR Wallingford, 2007)

A sediment budget from Southampton Water was developed through combining historical data and numerical model outputs. The historical datasets covered changes in intertidal and subtidal volumes and demonstrated that significant import of sediment from the Solent must be occurring to achieve a balanced sediment budget. Refinements to the budget were achieved through incorporating morphological modelling outputs to address the incomplete survey coverage of the estuary bed in historical datasets.

The sediment budget concept was first introduced by Bowen and Inman (1966). It was based on a consideration of:

- beach profiles
- estimates of littoral drift using the longshore component of wave power from hindcasts
- geological maps
- published literature (including climatological influences)

To balance their budget, Bowen and Inman divided the coastline into 5 cells with boundaries determined by positions where longshore transport had been estimated. This work remains as a good practical example of developing a sediment budget, as well as identifying many of the potential limitations in the approach.

The underlying principle for SBA is simply a continuity condition (that is, the conservation of volume or mass for a defined system). This system may be an estuary, a coastal cell or a series of such features covering a region of interest. In the example of a beach, the continuity may largely be one dimensional along the shore. Conversely in an estuary, pathways to establish continuity may be very complex with multiple directions. This complexity increases further if consideration is given to different sediment types such as muds (which are cohesive) and sands/gravel (which are non-cohesive) that can be part of the same system but may or may not mix in some stores, as these can be mobilised and transported in different ways. Furthermore, the time horizon over which the system is looked at can determine if, for example, a beach ridge is part of a store, sink or source.

3 When should SBA be used?

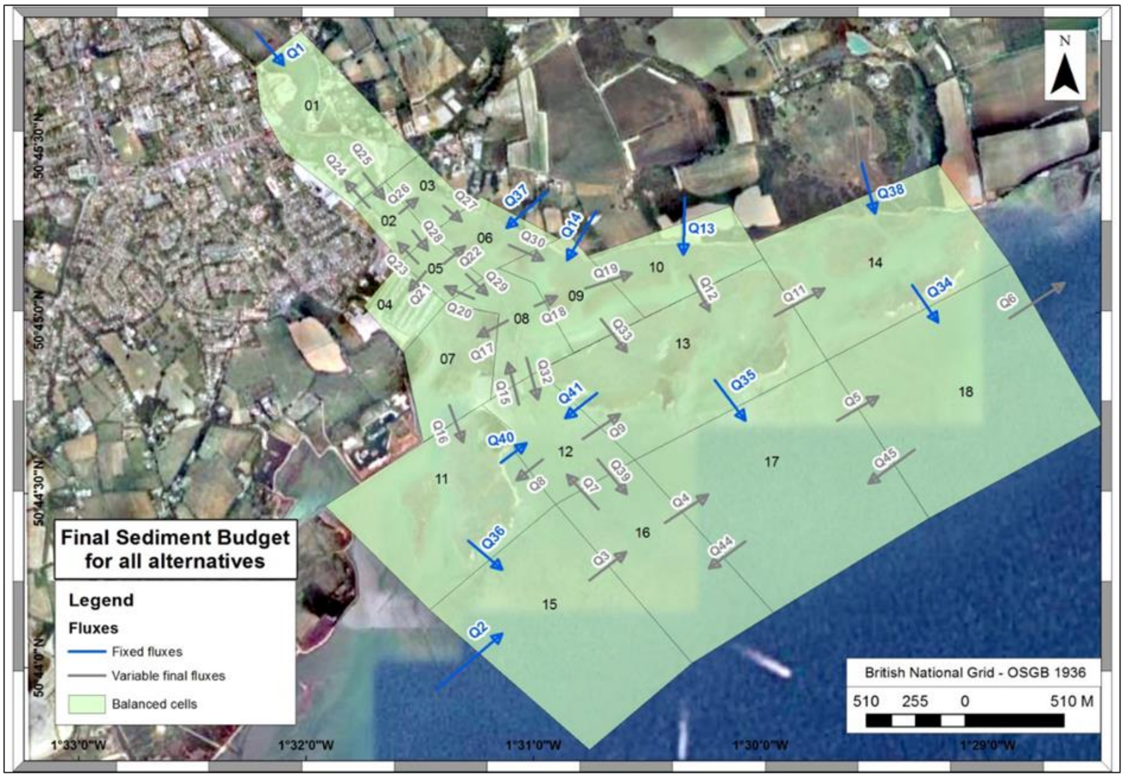
3.1 Introduction

SBA can be applied to any coastal sedimentary systems including estuaries composed of fine (mud size) sediments (see, for example, Townend and Whitehead 2003, de Castro Silva 2014; Box 3) and open coast littoral systems most typically composed of sand and gravel size sediments (see, for example, Dan and Vandebroek 2017).

SBA is typically used to provide a useful means of establishing the overall context for managing sediment volumes for a specific area and activity. Once a sediment budget has been developed, values in the budget may be altered to explore possible erosional or accretionary aspects of a proposed engineering project, or variations in assumed parameters.

It is not appropriate to definitively state when SBA should be applied. However, the following examples represent situations where SBA will be of value when there is a requirement to:

- understand the options for adjusting SMP policies and management options
- gain a quick and relatively inexpensive characterisation and quantification of sediment transport
- visualise the coastal processes from limited information
- simplify modelling outputs and complex studies into simple visualisations
- present analysis from lots of monitoring information, collating all past and potentially disparate information, and translating it to a common base
- capture changes between different beach sections over time and/or significant ‘in system’ variations
- sense check the evidence behind existing shoreline management policies and identifying the potential need for a change in policy or approach to delivery
- identify data gaps and uncertainties as well as supporting the scoping of future work



Box 3 Sediment budget for the Lymington River (de Castro Silva, 2014).

de Castro Silva (2014) used sediment budget analysis to further understanding of the causes of morphological change within the Lymington River. The study utilised detailed GIS analysis to help quantify the volumetric changes (ΔV), defining sources, sinks and pathways of sediments, providing a sediment budget and calculating filtering efficiency, settling velocities and sedimentation rates. The sediment budget showed that a significant amount of sediment is exported from the system, with ongoing change probably due to the lack of accommodation space within the estuary.

According to Rosati (2005), SBA serves as a common framework to:

- evaluate alternative project designs
- develop an understanding of sediment transport pathways through time
- estimate future rates of sediment accretion or erosion

The typical projects and initiatives where SBA could usefully be applied are:

- coastal management
    - coastal defence
    - strategic planning
    - beach management
- aggregate/ dredge disposal studies

If large offshore developments such as wind farms are situated sufficiently close to the coast so as to significantly alter the nearshore wave – and therefore the sediment transport – regime, SBA could be a useful tool for determining the potential for morphological change.

The development of a sediment budget may reveal both intra-annual positive and negative exchanges at a boundary (or within a cell), such as with the open sea or the updrift/downdrift boundary of a beach. Where this information is developed, useful insight may be gained by examining the relative balance between positive and negative exchanges to help support the argument of a net flux value. For example, a boundary condition that may have a relatively low net flux may be in fine balance between larger positive and negative fluxes. Where these fluxes are derived from wave driven forces there may be much greater variability and uncertainty, with a slightly different series of wave directional events producing an entirely different outcome.

Not every examination of an estuary or coastal system will require SBA and in some instances the high uncertainty with the results may mean SBA has limited value. For those situations, other forms of analysis – involving assessment of hydrodynamic, wave and sediment transport – may be more suitable. In summary these are:

- coastal settings where there is significant offshore–onshore sediment exchange, especially with sand bank systems
- where detailed understanding is required with regard to the mechanisms that are moving sediment around a system
- where information is required regarding the conditions under which sediment transport occurs
- where activities may impact the natural sediment pathways but not alter the balance of inputs and outputs from the system

3.2 Sediment cells

Motyka and Brampton (1993) identified 11 coastal cells around the coast of England and Wales. These provide the foundation for the SMP areas (Figure 3.1). HR Wallingford (1997) provides equivalent details for Scotland.

Each sediment cell is generally considered to be a closed system, which suggests that no sediment is transferred from one cell to another. The boundaries of sediment cells are determined by the topography and shape of the coastline. Large features, like peninsulas, act as large natural barriers that prevent the transfer of sediment. In reality, however, it is unlikely that sediment cells are fully closed. With variations in wind direction and tidal currents, it is inevitable that some sediment is transferred between cells or offshore. There are also many sub-cells of a smaller scale existing within these (major) cells. Sediment budgets for some of these cells (and sub-cells) have been derived through the corresponding SMPs, with the sediment budgets for the shingle beaches in the south-east having been recently compiled using extensive monitoring data (see Box 1 in Section 2).

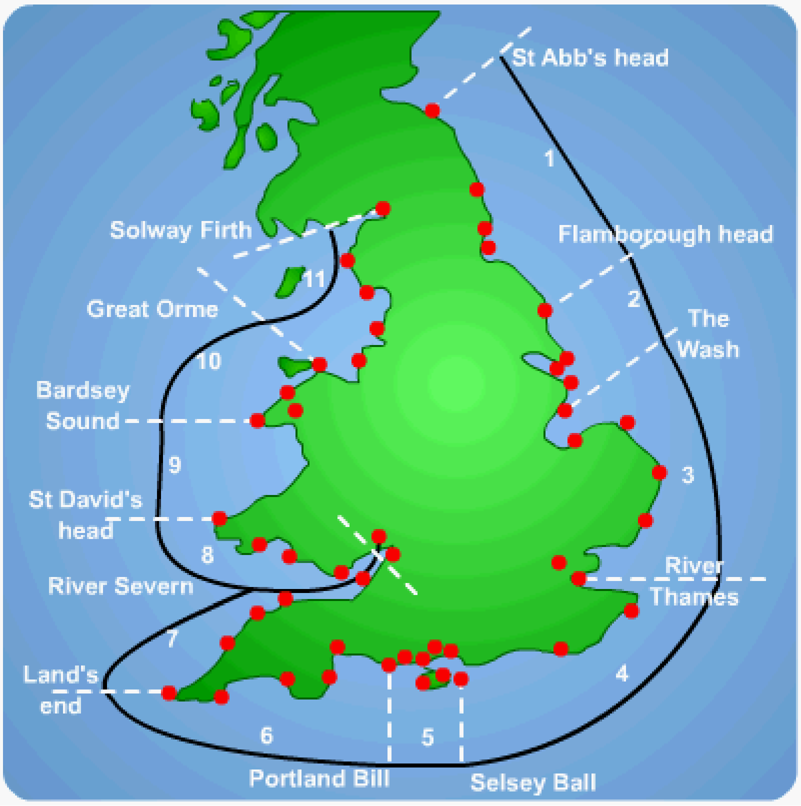


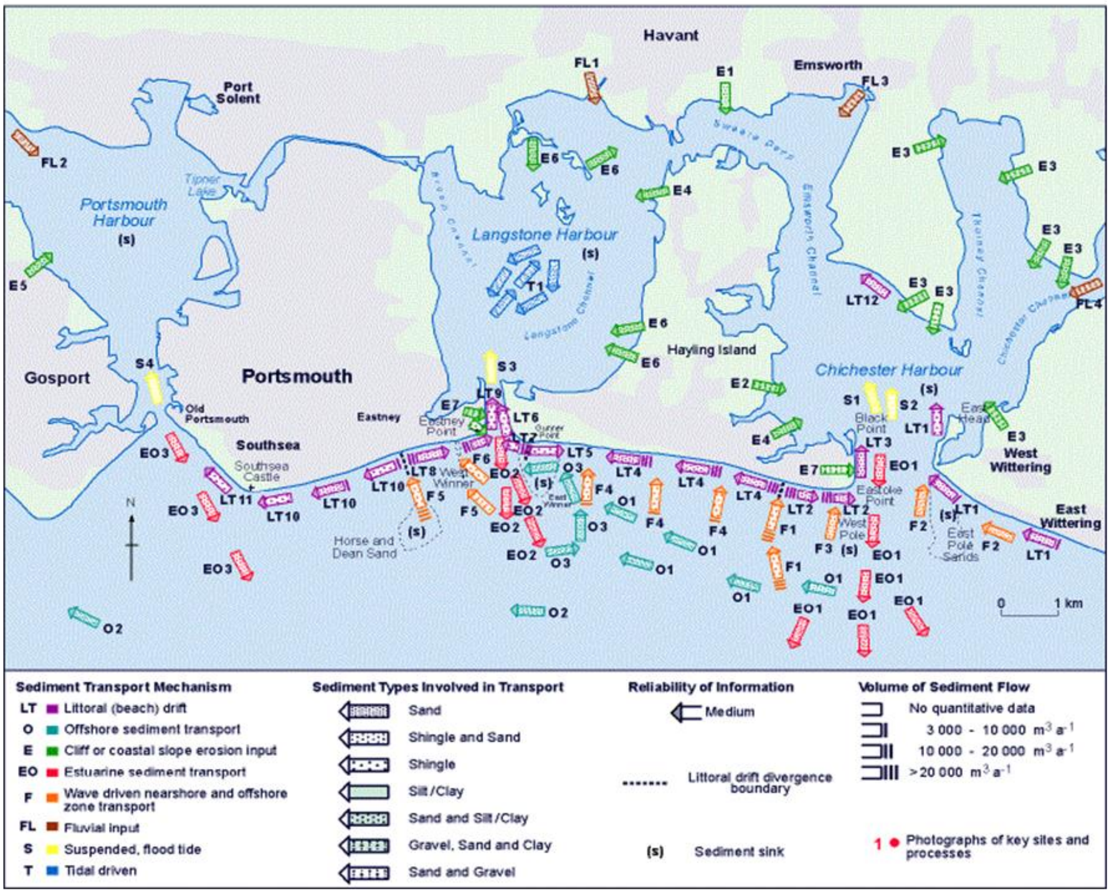
Figure 3.1 Littoral cells and SMP units around England and Wales

Source: http://thebritishgeographer.weebly.com/coastal-processes.html

Ideally, the sub-regional and local scale approaches can be positioned within a larger scale regional sediment budget, should that exist (Appendix A). Regional sediment transport studies are important to set the context for more detailed project level SBA studies. These studies typically identify relationships between the coastline and offshore features and sediment pathways. They include the following research initiatives:

- Southern North Sea Sediment Transport Study (southern North Sea)
- Standing Conference on Problems Associated with the Coastline (SCOPAC) Sediment Transport Study (English Channel) (Box 4)
- Cell Eleven Tidal and Sediment Transport Study (CETaSS) (north-west England and north Wales)
- Marine Aggregate Regional Environmental Assessment (MAREA) initiative

The availability and potential utility of these types of studies is reviewed in Appendix A.



Box 4 Sediment pathway map for Portsmouth, Langstone and Chichester Harbour (New Forest District Council, 2017)

The SCOPAC Sediment Transport Study area spans the coastline between Start Point, Devon and Beachy Head, East Sussex. The original study was published in 2004 and was an invaluable tool in development of the second round Shoreline Management Plans. The study area is broken down into 27 sediment unit maps such as that above for Portsmouth, Langstone and Chichester Harbour. Each map illustrates sediment type, direction, volume, transport mechanism and reliability of information. It is noted here however, that this study is not a true example of sediment budget analysis: no attempt is made to 'close' the cell, with volumes of sediment flow also often not directly linked to measured data.

The link from the regional scale to the local scale sediment budget can be considered as a downscaling exercise that provides delivers additional levels of detail, understanding and improved levels of confidence which would not be possible or practical at the regional scale. An important contribution from the regional sediment budget will be in helping to define suitable boundaries for the local scale application, both in terms of location and quantification.

In the majority of cases, the SBA will be an important component within a larger assessment of the hydrodynamics, wave climate and sediment transport studies. The process whereby input parameters are determined is typically iterative, with regional scale studies often informing model input parameters and model outputs subsequently used to inform more detailed (local scale) SBAs.

4 How to apply SBA

4.1 Sediment budget equation

In its most basic form, the sediment budget equation can be written as follows:

[Total sediment inputs] – [Total sediment outputs] = [Net change in sediment volume within the system]

Equation 4.1

The choice of volume or mass as a base unit is likely to relate to the type of system being investigated, as follows:

- **Definition of changes in volume within the defined area to give a balance.** This is applicable to non-cohesive (that is, sand and shingle) shores, where suspended sediment concentrations are low and material types remain similar.
- **Definition of exchanges in mass to and from the water column to give a mass balance**. This is more straightforward in relation to systems with cohesive (that is, muddy) or mixed sediments, large suspended sediment concentrations and higher degrees of variability in the sediment dynamics within the system, as is the case with the Severn Estuary, for example.

For some complex situations, the budget may be considered separately for sand/shingle and mud. In such cases, however, the units should remain the same.

The sediment budget relationship may also sometimes be written as follows (Rosati and Kraus 1999); this is the same relationship described by the US Army Corp of Engineers in its Sediment Budget Analysis System (SBAS) tool[2] (Kraus and Rosati 1999, Rosati and Kraus 1999, Rosati and Kraus 2001):

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual$$

Equation 4.2

where:

$\sum Q_{source}$	=	sum of all inputs to the system / total sediment inputs
$\sum Q_{sink}$	=	sum of all outputs from the system / total sediment outputs
ΔV	=	net volume change within the system / net change within the system
P	=	any additional positive contributions within the system, such as beach recharge
R	=	any additional negative interventions within the system, such as dredging
Residual	=	Degree to which system is balanced (equals to zero if system is in equilibrium)

Equation 4.2 is presented schematically in Figure 4.1. In this equation, the units for each parameter are typically volume (for example, m^3 and more probably 10^6 or M m^3 since the quantities involved will often be very large), with values determined as the net quantity over an appropriate period. The base unit can also be taken as mass (for example, tonnes); this tends to be more appropriate in cohesive (that is, muddy)

[2] The SBAS tool is a Windows application which runs through ArcGIS. It provides a framework for formulating, documenting and calculating sediment budgets, including estimation of uncertainty. SBAS is the most readily available and perhaps best known tool for undertaking SBA.

sediment systems where large amounts of sediment may be held in the water column and would remain impractical to measure as a volume. The conversion between mass and volume (for solids) remains possible with knowledge of the bulk density of the various sediment accumulations.

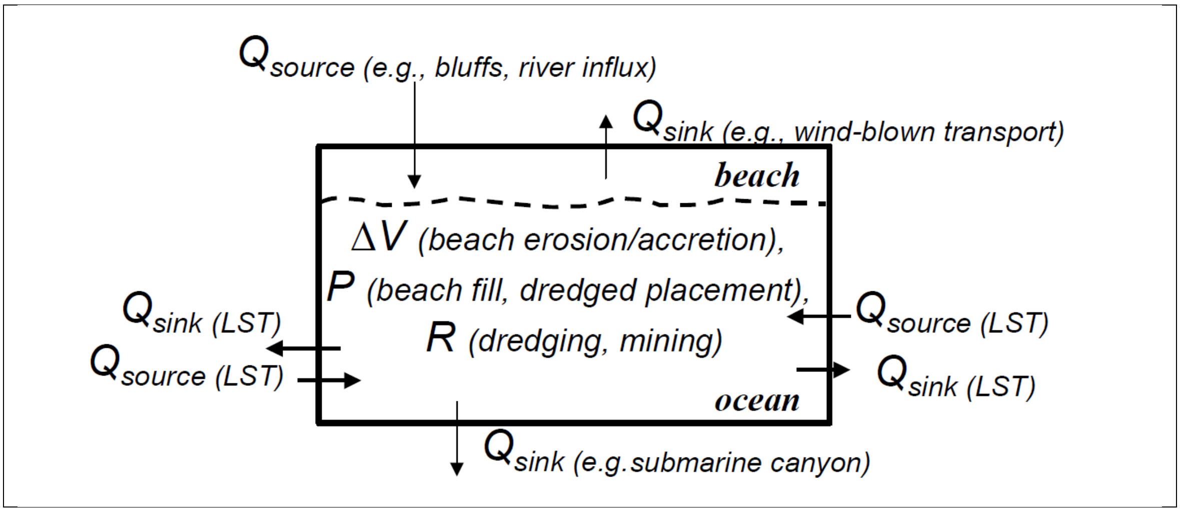


Figure 4.1 Schematic of sediment budget based on Equation 4.2

Notes: LST = longshore sediment transport
Adapted from Rosati and Kraus (1999)

4.2 Representing processes and components

Developing conceptual understanding from existing literature is recommended before deriving the sediment budget. This process is iterative, with SBA both being informed by and used to develop conceptual understanding.

First, it is important to establish the area of interest so that a system approach can be developed. Boundaries should be selected where known conditions can be established and which are also sufficiently distant from any activity that may be the subject of change due to development activity. 'Null' boundaries (where no sediment transfer occurs) are ideal, such as drift divides on the coast or prominent headlands which restrict longshore transport.

Second, the contributing features (that is, components of the sediment budget) to any sediment exchanges within the system should be identified, as well as the suitable structure for any sub-system divisions. The structure of both should remain relatively simple and also relate to the level of available data to inform the budget.

4.3 Consideration of spatial scale

If the requirement is to develop a regional scale sediment budget then the level of detail should be simplified, as appropriate, since a broader overview is likely to be sufficient.

Ideally, a local scale sediment budget for a specific area of interest will offer a higher level of detail suited to the specific requirements of the investigation and be able to link with the structure of any associated regional budget. This link between the local and regional scale was successfully achieved by the East Kent Engineering Partnership and Canterbury City Council in their shingle SBA for the coastal frontage between Seasalter (north Kent) and Selsey Bill (West Sussex) (see Box 1 in Section 2).

A common application of sediment budgets is in nearshore coastal areas and estuaries. Table 4.1 indicates suitable scales.

Table 4.1 Application of sediment budgets

Type of area		Scale
Open coast	Alongshore	~1km lengths, coastal sub-cells or survey units, linked to existing structures
	Cross-shore	Cliffs and dunes – order of a few metres landwards from cliff edge
		Beaches – back of beach or highest astronomical tide (HAT) to mean low water springs (MLWS) (typically a few tens to a few hundred metres on low gradient beaches)
		Subtidal – MLWS to depth of closure
Estuaries		~500m channel lengths and extending to HAT

4.4 Consideration of temporal scale

As well as setting out the spatial framework for the sediment budget, the temporal interval should also be confirmed. This will be dictated to a certain degree by the time intervals for which data are available.

The temporal interval is often selected as an annual interval (ideally summer to summer such as July to June), since this will include a full cycle of seasonal influences, losses and gains to help derive a net value. Some consideration may need to be given as to whether the period of analysis represents an atypical year or if there are important inter-annual variations. Such variations may be random, cyclic, contain a trend or involve a combination of such effects. They will contribute to increased uncertainty if not adequately accounted for (Section 6).

An alternative time interval to the commonly used annual time frame is possible, should this be required. This may be decadal to consider a longer term balance or shorter if there was a need to partition, for example, at the level of spring and neap tides or summer/winter. In addition, a sediment budget may need to be revised or updated if any of the sediment exchanges become modified by natural influences or new developments.

SBA may provide a useful means to test possible long-term (decades or more) morphological evolution of a system. This includes the ability of the system to adjust to sea level rise. Indeed, coastal and estuarine systems are typically highly complex, meaning that the uncertainty associated with predictions of future coastal evolution derived from bottom-up[3] process driven models is typically very high. Instead, top-down[4] morphological form models based on SBA may offer a more practical solution for consideration of long-term change to coastal systems (including estuaries) (see, for example, Pethick 1994, Cooper et al. 2001).

[3] An approach that builds on field interpretations of processes to understand individual system components. In general, bottom-up methods are designed to reproduce short-term changes at a detailed spatial level.
[4] An approach based on 'big picture' geomorphic understanding of coastal and estuarine processes, and controls on them including sea level rise, sediment supply and geology. Typically guided by expert judgement and often informed by consideration of other similar systems.

4.5 Consideration of sediment type

A regional scale application is likely encounter multiple sediment types and it may be necessary to consider splitting the budget between a version for cohesive and non-cohesive sediments. Conversely, a local sediment budget may focus on a single sediment type, for instance, the shingle SBA for the coastal frontage between Seasalter (north Kent) and Selsey Bill (West Sussex) developed by East Kent Engineering Partnership and Canterbury City Council (see Box 1 in Section 2).

5 Using data to solve the sediment budget equation

5.1 Introduction

The compilation of an overall sediment budget brings together a variety of data types for the different elements making up the budget such as volumes of beach erosion or rates of longshore sediment transport. Some of these data may be drawn directly from monitoring surveys, while other data may require some form of derivation or deduction.

Understanding the potential limitations of these data – both in terms of their accuracy and the degree to which they can be used to adequately characterise variability within the location and time period of interest – is critical to enable users to understand the reliability of values within the budget. Guidance is provided in Section 6 on to how to account for and manage uncertainty.

The identification and quantification of all the mechanisms giving rise to sediment transfers within the system can be difficult, and for the most part will only be approximate estimates of sediment exchange between sources and sinks. Data will be compiled for a variety of different features making up the budget, ideally with most of the data being drawn directly from monitoring surveys and field sampling (that is, primary data). Inevitably, the availability of suitable primary data may lead to some shortfalls (that is, limitations in the overall dataset), either in data coverage or periods of monitoring. In such cases, a sediment budget is still possible, but may require development of secondary data. Secondary data can be generated by:

- use of numerical models
- simple data extrapolation (that is, extending data beyond the original range of information)
- interpolation (that is, gaps infilled between a sparse spatial or temporal coverage)

The sequence of developing a quantity for the sediment budget should always start with the more straightforward components, especially when these can be derived directly from primary data.

This section provides an overview of the most important primary and secondary data available within the UK, and offers guidance as to how this information can be used within an SBA. Typical survey methods, accuracy, resolution and availability are summarised in Table 5.1, with further details on the available data being provided in Appendix B. Section 6 considers the implications of data accuracy to overall levels of uncertainty.

For all SBA studies, it is recommended to first undertake a literature review to identify the regional and sub-regional studies described in Appendix A.

Where a specific type of data is compiled that includes older records as well as new records, the likelihood is that the ‘precision’ is higher in the new record due to improvements in measurement techniques. Precision in this context is the ability to quote a value to higher level of detail, such as from 1 to 2 decimal places. This precision may relate to position fixing in the horizontal plane since the advent of global positioning systems (GPS) and the vertical plane with the improved capability of modern instruments. Where the series of data is examined to develop an inter-annual variation for the whole period, the precision of the least precise data should apply to the whole dataset.

Table 5.1 Survey methods for primary sediment budget inputs

Survey method	Spatial resolution	Accuracy	Frequency	Regional availability
Beaches				
RTK GPS surface	Medium	High	High	High
Laser scanning	High	High	Medium	Low
LiDAR (terrestrial)	High	High	Medium	High
Photogrammetry	High	Medium	Low	Low
Profiles	Medium/Low	High	High	High
Cliffs and dunes				
RTK GPS	Medium	High	Low	Medium
Laser scan	High	High	Low	Low
LiDAR (terrestrial)	High	High	Medium	High
Photogrammetry	High	High	Low	Low
Ortho-photography	Medium	Medium	Medium	High
Subtidal (open coast, estuaries and rivers)				
Swath bathymetry	High	High	Low	Medium
Single beam	Medium	High	Medium	Medium
LiDAR (bathymetric)	Medium	Medium	Low	Low
Water column				
Turbidity meters	Medium/Low	Medium	Low	Low

Notes: LiDAR = light detection and ranging; RTK = real time kinematic

5.2 Data considerations

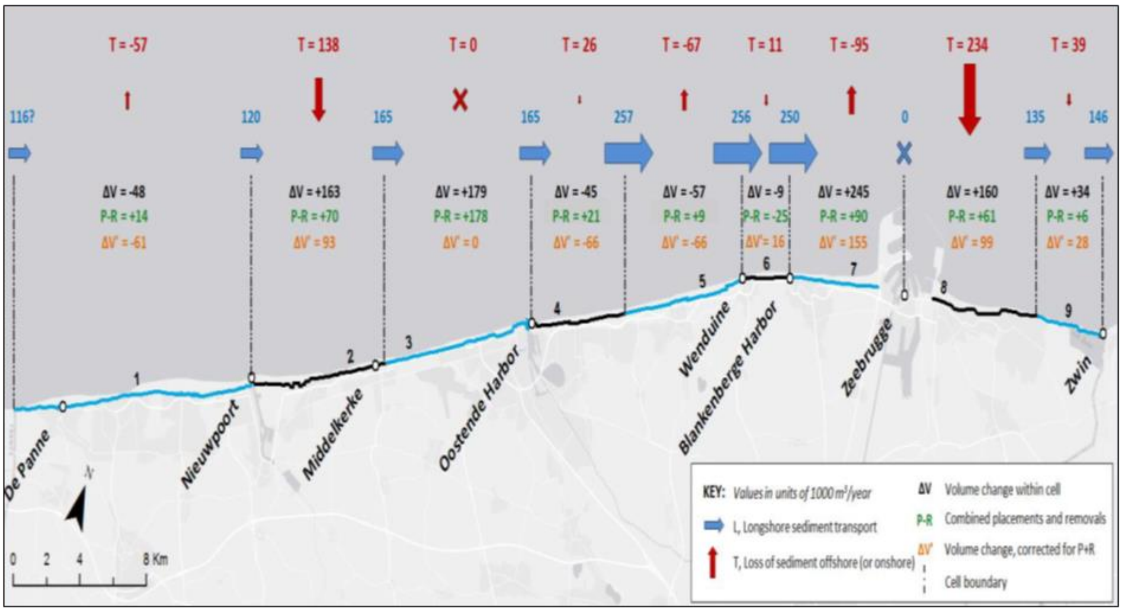
This section examines in more detail the various primary and secondary datasets outlined in Section 5.1 and sets out how they may be used to quantify the separate elements of the sediment budget described in Equation 4.2 and Figure 4.1.

5.2.1 Net volume change within the system (Δ)

Budgets typically start from documented accretion and erosion to estimate other contributions with higher uncertainty (Rosati 2005). Ostensibly, beach volume changes are the most straightforward element of the sediment budget since topographic surveys have a long history of data collection in the UK. This long history of primary data collection is important since the beach profile data used to develop the budget needs to be available for a long enough period to help explain both inter (that is, from year to year) and intra-annual (that is, within a year) variations in beach form and seabed profiles.

In England, the Regional Coastal Monitoring Programmes generally provide a minimum of an annual survey of all accessible beaches and up to 3 surveys per year in areas where beaches are highly managed. Surveys from GPS, laser scanning, LiDAR and more recently photogrammetry (for example, by drones) will provide typically a 1m or 2m resolution surface (gridded) data, so a change in volume can be obtained by subtracting one measured surface from another. If surface (gridded) data are not available, a fairly reliable estimate of beach volume can be obtained from beach profiles by multiplying cross-sectional area changes by a representative alongshore length.

Comparisons between beach topographic data can be used to calculate LST rates by dividing the beach into smaller compartments for which net volume change may be calculated. Annual sediment transport rates can also be obtained for a sediment budget from secondary data sources, in particular numerical modelling (see for example, Dan and Vandebroek 2017; Box 5). However, these estimates of potential sediment transport should ideally be validated using primary field data, especially if the sediment modelled is different from sand.



Box 5 The sediment budget for the entire Belgian coast for the period 2000 to 2009 (all volumes are in 1000 m³) (Dan & Vandebroek, 2017).

Dan and Vandebroek (2017) developed a sediment budget for the highly developed Belgian coast. The nearshore system, confined offshore by the closure depth and onshore by human structures, was divided into 9 coastal cells, mainly based on the variations in the gradients of the longshore transport. These cells were analyzed using available information such as bathymetric and topographic surveys, placement and removals of sediment by human intervention, sediment deficit created by sea level rise, and estimates of longshore transport derived from numerical modelling.

A major stumbling block for many sediment budgets is the subtidal zone below MLWS. For many beaches, this area is closely linked to seasonal changes in overall beach volume but is seldom quantified due to the difficulties (and hence expense) of shallow water bathymetric surveying, particularly of regions such as flood and ebb deltas near harbour or estuary inlets.

Swath (multibeam) bathymetry provides the most detailed primary data for quantifying movement of banks and deltas. A further advantage is that these surveys can also identify areas of rock, sediment, sand banks and sand waves, and hence provide useful clues as to subtidal mobility and net transport direction.

By March 2018, around 70% of the English coastline will be covered by freely available International Hydrographic Organisation Order 1A swath bathymetry at 1m or 2m resolution from surveys conducted by the Maritime and Coastguard Agency's Civil Hydrography Programme or the Regional Coastal Monitoring Programmes.

However, there are few areas with the repeated swath bathymetry needed for difference modelling. In their absence, an estimate of seabed mobility can be obtained from comparison of historic charts, preferably using fair sheets (soundings), though the percentage errors are likely to be high. In the absence of measured information on bed level change, an estimate can be made from modelling long-term tidal currents to derive residual transport directions and rates. This secondary data can be obtained either using a hydrodynamics model (for example, POLCOMS) or a model including sediment transport (for example, MIKE 21). Supporting tidal elevation data for validation of the harmonics are available for the 44 sites of the National Tidal and Sea Level Facility.

5.2.2 System inputs $(\sum \boldsymbol{Q_{source}})$

The most appropriate survey methods for measuring cliff inputs depend to a large degree on the cliff geometry. In general, cliff inputs are most accurately derived from repeated laser scan surveys of the cliff face, although these surveys are not widely captured at present. However, where cliffs are sloped, downward looking survey techniques such as LiDAR and photogrammetry are able to characterise the topography of the cliff face. Contributions from cliff erosion over longer timescales may also be deduced from historic maps.

A fundamental in determining input from cliffs is knowledge of the composition of the cliff (for example, the relative contribution of fine and coarse material.) Indeed, uncertainty in cliff composition may lead to greater inaccuracy in determining the net supply of beach material than that associated with uncertainty in the cliff retreat rate.

The iCOASST project (2013 to 2016) has made the open source version of SCAPE+ (Soft Cliff And Platform Erosion) freely available. These secondary data may be of use to help determine and predict the future contribution of cliff material into a system. More generally, the iCOASST framework/models can be used to better understand sediment budgets (conceptually using the Coastal Estuarine Systems Maps) and in more detail using the strategy scale models.

For systems that include contributions from rivers (as is common in many large UK estuaries), information is required to help establish a sediment discharge (input). This can be based on the product of fluvial discharge and sediment concentration. Similarly, for systems with an open boundary with the sea such as at the estuary mouth, then discharge (flux) measurements are needed.

The National River Flow Archive (NRFA) is the UK's focal point for river flow data. This collates, quality controls, and archives hydrometric data from gauging station networks across the UK including the extensive networks operated by the Environment Agency (England), Natural Resources Wales, the Scottish Environment Protection Agency and the Rivers Agency (Northern Ireland).

Sediment concentration information is more limited in river systems than discharge values, and may also vary greatly in magnitude. For example, the intra-annual variation of river flows may follow a typical seasonal pattern, the detail of which is not visible in simple average value statistics, such as mean or 50% exceedance flow values. The issue here may be that 90% of the sediment input from a fluvial source may happen only during the 10% exceedance spate type events. Some knowledge of the catchment behaviour, landforms subject to drainage and the local climatology therefore needs to be considered when applying discharge values with sediment concentrations to deduce an average value from fluvial sources for the time period of interest. Care should also be taken when referring to river gauges that are high up in catchments and which do not account for any additional contributions from the lower catchment.

In general, finer grained sediments that can remain in suspension for days to weeks (for example, muds in the turbidity maxima in the Bristol Channel) are of less significance for sediment budgeting since the time span of the budget may blur their net variation. Records of sediment in suspension measured by turbidity meters do exist, but are usually short term (weeks) and isolated.

*Positive system contributions **(P)** associated with management practises,*

Beach recycling and replenishment logs are kept by operations managers and can be quantified for use in sediment budgets.

5.2.3 System outputs $(\sum \mathbf{Q}_{\mathbf{sink}})$

In areas with extensive sandy beaches, wind-blown sand being removed from the beach can prove to be of some significance; where dunes are present, build-up of the dune crest or front (from LiDAR) may provide some information about the losses to the beach. Alternately, an estimate may be derived from beach operations to remove sand from promenades or roads behind the beach.

*Negative system contributions **(R)** associated with dredging*

For systems with licensed maintenance dredging (that is, to maintain access through approach channels and at harbour berths) and disposal sites, the associated data can be obtained from the local port(s) or with reference to annual Food and Environment Protection Act disposal at sea values compiled for Defra for England and Wales. Capital dredging projects will typically have an associated environmental impact assessment (EIA), with the volumes of material involved provided in publically available documents.

For systems with licensed mineral extraction sites of marine aggregates, annualised quantities of removal and areas involved are published on an annual basis by The Crown Estate and are available to download.

6 Managing uncertainty

As described above, SBA is very data hungry and in many cases assumptions, estimates, data manipulation and the use of secondary data will be required. Uncertainty associated with values provided by SBA may arise from:

- methodological assumptions
- input data error and inaccuracy
- natural variability including unknowns in the measurement process

These elements are summarised below. A method for quantitatively accounting for this uncertainty based on a root mean square approach is set out in Rosati (2005), with worked examples also included.

As part of the uncertainty reporting process, the number of 'residuals' in the budget should be commented on. The residuals can be defined as the values within the sediment budget that can only be estimated as the balance against the other known (measured) contributions. These residuals are likely to represent the budget components with the lowest confidence and issues that should be studied in further detail in due course.

6.1 Methodological assumptions and limitations

Throughout the process of developing a sediment budget for a specific area, a number of assumptions may be made which contribute to overall uncertainty. Some of the important assumptions and limitations are summarised below.

- Each sediment cell on which the sediment budget is based is generally considered to be a closed system. This suggests that no sediment is transferred from one cell to another. In reality, however, it is unlikely that sediment cells are fully closed.
- It is often difficult to ascertain and define all of the possible ranges of sediment transport pathways, as well as their relative magnitudes. For instance, it is typically the case that assumptions have to be made about the amount of transport occurring through and around structures such as groynes.
- Some assumptions will have to be made to convert all the data used to compile a sediment budget to either mass or volume. This usually entails defining a bulk density, sediment particle density and water density to convert from dry solids (mass) to volume or vice versa.
- The closure depth typically defines the seaward boundary of beach units considered in SBA. This is often difficult to define in the absence of multiple repeat surveys covering a long period of time.
- Some sediment budget inputs can be difficult to derive from observations (for example, net flux from or to the sea in wide estuaries and the extent of erosion of intertidal areas resulting from wave action). It may therefore be necessary to derive these values by balancing the budget and providing data for all the other budget contributions. This may not be possible and therefore the derivation of these contributions may require in-depth analysis, numerical modelling of sediment transport and/or further data

collection to determine the sediment contributions (ABPmer and HR Wallingford 2007).

6.2 Input data error and inaccuracy

The quantities for each element of the sediment budget are each subject to potential errors due to the accuracy of the measurement system. For example, laser scan and RTK GPS surveys have a vertical accuracy of ±0.03m, while the highest order swath bathymetry has a vertical accuracy of ±0.2m (Table 6.1). Although it is to be hoped that the measurement errors are randomly distributed and therefore may cancel out, an allowance should be made for the potential reliability of the budget quantities.

Table 6.1 Indicative survey accuracy terms

Survey type	Vertical accuracy (m)
RTK GPS, laser scanning	±0.03
LiDAR (terrestrial)	±0.15
Photogrammetry	±0.15
Swath bathymetry	±0.20
LiDAR (bathymetric)	±0.30

Notes: The latest Environment Agency LiDAR surveys now achieve vertical accuracy of closer to 0.05m (Environment Agency 2016)

Common sediment budget calculation errors can include:

- not using the same LiDAR data type (for example, differencing 2007 unfiltered and 2012 filtered LiDAR data)
- using datasets with different resolution (for example, 1m and 2m) – the finer resolution data should be down-sampled to match the coarser
- not ensuring a common analysis area for both datasets being compared – data should be clipped to the area common to both surveys
- interpolating topographic surfaces from low density grids of point data (for example, that collected by GPS)

As stated in Section 5.2, modelled data can be used in the absence of field data as a means by which to quantify elements within a sediment budget. However, this information will be associated with its own error term, arising from uncertainty with both the input data and the model set-up. Calculation of sediment transport can be highly complex and associated with high levels of uncertainty (see, for example, Soulsby 1997). For instance, modelled rates of LST are commonly used in SBA yet these will be subject to uncertainty associated with (among other things) accurate characterisation of shoreline orientation within the model and adequate description of the nearshore wave regime. Typically, best practice involves the use of higher and lower model estimates as a sensitivity analysis in order to ascertain the range of values for a given parameter of interest.

Research by the BLUEcoast project (2016 to 2020) aims to reduce uncertainty in sediment budgets through monitoring and modelling physical and biological processes at a range of sites across the UK. These sites represent a range of sediment systems and include:

- exposed (high energy) sandy coasts with rocky headlands
- partially exposed (medium-wave energy) sand–shingle coast, with soft rock cliffs and subtidal sediment
- mixed sand–mud coasts and estuaries

Initial work at Perranporth has developed an approach to map the depth of bed rock and accurately position of the depth of closure. Continued work will focus on:

- assessing headland bypassing
- the role of biology within sediment exchange processes
- the development of models that parameterise both physical and biological processes to more accurately simulate long-term coastal evolution and shoreline recovery following storm events

6.3 Natural variability

In coastal processes, significant contributors to uncertainty enter through natural variability and unknowns in the measurement process. Rosati (2005) notes that this includes:

- temporal variability (daily, seasonal and annual beach change)
- spatial variability (alongshore and across shore)

Climate change is also expected to result in pronounced change along some coastlines, potentially altering (among other things) the intensity and frequency of storm events. Over longer timescales, this has the potential to influence each of the main elements making up a sediment budget, specifically:

- inputs (for example, cliff erosion and suspended sediment within rivers)
- outputs (for example, LST rates)
- stores (for example, beach volume)

This will be especially important when considered in conjunction with sea level rise.

Natural variability will exist in all environmental data, but may not always have an amplitude that is greater than the data's precision and accuracy. Such variability may also take a long succession of surveys before the signal can be deduced (for example, a period of many years).

Marine physical processes typically exhibit high amplitudes of natural variability. An example of this is the intra-annual rates of littoral drift, which may have a minimal level during calmer summer periods and a maximum level during winter storms. Inter-annual variability in drift rates – and patterns of erosion and accretion – may also be distinguishable and governed by factors such as the frequency, severity and directional influences of storm conditions from year to year. These factors may then also correlate to larger scale driving mechanisms such as the North Atlantic Oscillation or the 18.6 year lunar nodal cycle. Consideration of such cycles helps set into context the sample period for the data used to compile the sediment budget.

Variability may be accounted for in different ways, depending on the scale and nature of the variation in the dataset. While inter-annual variations within the estimate of a single mean net annualised value should not be overlooked, they also need to be expressed separately to any implied accuracy of the data/methodology. The use of standard deviation to represent natural variation around the mean may be helpful in this context. Where there is a high level of variability, the standard deviation may in some cases exceed the mean net value (that is, the variability is greater than the calculated volume). In these cases, higher and lower estimates representing the range in the net value should be applied as a sensitivity analysis in order to consider the full variability.

In some circumstances, it may be necessary to extrapolate a trend from existing data (for example, to generate reliable data for a missing period or a time in the future) using linear regression. The resulting R^2 value (coefficient of determination) can be used to provide understanding of the goodness of fit between variables. Importantly, extrapolation should be treated with considerable caution if R^2 is less than 0.49 as this suggests that 51% (that is, the majority) of the data are not conforming to any trend.

7 Key messages

Sediment budgets are of central importance when managing the coast, as they are used to establish the overall context for managing sediment volumes for a specific area and activity. Once a sediment budget has been developed, values in the budget may be altered to explore possible erosional or accretionary aspects of a proposed engineering project, or variations in assumed parameters.

The ‘conceptual understanding’ of a system describes how the physical processes link together and evolve in response to applied forces. SBA represents the quantification of the conceptual understanding for sediment movement. Not every examination of an estuary or coastal system will require SBA an, in some instances, the high uncertainty within the results may mean SBA has limited value.

The concept of sediment budgets will become increasingly important as we seek more innovative approaches to shoreline management and to understand natural system adaptation to climate change.

The compilation of an overall sediment budget brings together a variety of data types for the different elements making up the budget such as volumes of beach erosion or rates of longshore sediment transport. Some of these data can be drawn directly from monitoring surveys, while other data may require some form of derivation or deduction. Understanding the potential limitations of these data – both in terms of their accuracy and the degree to which they can be used to adequately characterise variability within the location and time period of interest – is critical to enable users to understand the reliability of values within the budget.

Data will be compiled for a variety of different features making up the budget, ideally with most of the data being drawn directly from monitoring surveys and field sampling (that is, primary data). Inevitably, the availability of suitable primary data may lead to some shortfalls (that is, limitations in the overall dataset), either in data coverage or periods of monitoring. In such cases, a sediment budget is still possible, but may require development of secondary data such as numerical modelling results which will also contain inherent uncertainty.

The sequence of developing a quantity for the sediment budget should always start with the more straightforward components, especially when these can be derived directly from primary data.

In coastal processes, significant contributors to uncertainty also enter through natural variability. Climate change is expected to result in pronounced change along some coastlines, potentially altering the intensity and frequency of storm events – among other things. Over longer timescales, this has the potential to influence each of the main elements of the sediment budget, especially when considered in conjunction with sea level rise.

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List of abbreviations

CETaSS	Cell Eleven Tidal and Sediment Transport Study
EIA	environmental impact assessment
CoRDDi	Coastal Research Development and Dissemination
FEPA	Food and Environment Protection Act
GPS	global positioning system
HAT	highest astronomical tide
LiDAR	light detection and ranging
LST	longshore sediment transport
MAREA	Marine Aggregate Regional Environmental Assessment
MLWS	mean low water springs
NRFA	National River Flow Archive
R&D	research and development
REA	regional environmental assessment
RTK	real time kinematic
SBA	sediment budget analysis
SBAS	Sediment budget analysis system
SCOPAC	Standing Conference on Problems Associated with the Coastline
SEA	strategic environmental assessment
SMP	Shoreline Management Plan

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

Glossary

Accretion	The gain in sediment volume measured over an area by an increase in level. Accretion at the coast may lead to an advance of the shoreline
Accuracy (of data)	The closeness of the derived value to the correct value
Balance	A balanced sediment budget will have inputs and outputs to the system that are equal. If the budget has a positive balance, then the system will be accretional. If it has a negative balance, it will be erosional which could lead to sediment demand.
Bathymetry	Topography of the seabed typically measured from a vessel
Best estimate	The value selected from a range of estimated values that is considered to offer the highest level of accuracy
Coastal cell	A bounded unit of coast within which the sediment is largely self-contained and does travel outside the boundary. Interruptions to the movement of sand and shingle within one littoral cell should not affect beaches in a neighbouring sediment cell.
Cohesive (sediment)	Fine sediment – such as muds and clays – that due to the small particle size allows the material to bind together.
Confidence limits	A pair of values (upper and lower) which bound the best estimate to indicate the range within which the best estimate is likely to be to the correct value
Demand	The balance between sediment demand and supply drives the evolution of the coast. When supply is greater than demand, the coast will grow seaward. When demand equals supply, the coast will stay in place. When the supply is insufficient, the coast will tend to lower or retreat. Issues such as sea level rise may increase the sediment demand and if not met by sufficient supply could result in coastal retreat
Epoch	A period representing several years grouped together
Erosion	The loss in sediment volume measured over an area by a reduction in level. Erosion at the coast may lead to a retreat of the shoreline
Estimate	An approximation of a parameter without direct measurement
Exchange	See flux
Feature	A component part of the system such as a morphological unit
Flux	An exchange of sediment across a boundary (in or out)
Gross	Total amount of sediment exchanged in or out of a cell without any deductions
Input (credits)	Supply of sediment into a coastal system from an external source
Inter-annual	A variation that occurs between years

Intra-annual	A variation that occurs within a year
Limitation	The point between a permitted use (within limits) and outside a permitted use (beyond limits)
Littoral	A process that acts along the shoreline
Local	A close examination of a specific area or issue
Pathway	The directions which sediment can move in and out of a cell. The mechanism for transporting sediment along the pathway may be due to wave or tidal process, or a combination of both. Although the presentation of pathways is commonly applied to the net transfer, the contributing mechanisms such as ebb and flood phases of the tide may also have contrasting pathways that aggregate to define the net pathway.
Precision	The level to which a value can be expressed without implying false accuracy
Primary (data)	Data that can be directly determined from measurement
Net (estimate)	The balance of sediment exchanged in and out of a cell accounting for all deductions for a defined (closed cyclic) period, typically reduced to an annualised value
Non-cohesive	Coarse sediments types – such as sands and shingle – that have particle sizes large enough to overcome electromagnetic forces to act individually
Outputs (debits)	The removal of sediment from a coastal system
Qualitative	Providing a descriptive statement
Quality (of data)	How useful the data are to the intended application. High quality is preferable; low quality can still be useful with stated reservations but poor quality is unlikely to have any value.
Quantitative	Providing a specific value
Regional	A broad general examination over a large area providing an overall framework to establish local scale relationships
Reliability	The degree to which data remain useful and can be relied on (for example, low quality data are unlikely to offer any reliability in their application)
Secondary (data)	Data that are derived by means other than measurement, such as the use of modelling tools
Source	A location that contributes sediment into a system, such as a river
Sink	A location that removes sediment from a system
Store	A location that may be able to receive and hold onto sediment, but may also subsequently contribute sediment back to the system under certain circumstances
Sub-cell	A sub-division of a littoral cell within which sediment movement may be independent or weakly dependent on each other
System	The macro unit which contains all the functioning elements and

	sub-systems to explain the behaviour of an area of coastal and which can be schematically represented in a system diagram
Output	The removal of sediment from a system
Uncertainty	Unknowns that may influence the width of confidence limits
Variance	The amount of spread in the data population away from the mean

Appendix A: Regional sediment transport studies

A.1 Overview

Around UK waters there are a collection of regional scale sediment transport studies that may have been developed prior to the formulation of SMPs, specifically to support SMPs or for other coastal management requirements, such as the assessment of marine aggregate dredging.

Regional sediment transport studies are important to set the context for more detailed project level SBA studies. By definition, the regional scale will cover a large body of water and long length of coastline such as the southern North Sea, the English Channel and the Irish Sea.

To date, a number of regional sediment transport studies have been commissioned as part of wider research initiatives. These include:

- Southern North Sea Sediment Transport Study (Southern North Sea)
- SCOPAC Sediment Transport Study (English Channel)
- CETaSS (north-west England and north Wales)
- MAREA initiative

Although very useful, these studies typically only identify broad directions of sediment transport and main source terms, with local level studies providing the detail regarding sediment budgets. Where a regional sediment budget has associated quantities, these should be considered indicative due to the uncertainty associated with using multiple datasets and the assumptions that will have needed to be made to address data gaps. The more important component of these regional studies is the overview of conceptual understanding to offer a qualitative statement and high level structure.

This appendix provides a brief review of this work in the context of supporting regional scale requirements for sediment budgets. The review follows the sequence of coastal cells established by Motyka and Brampton (1993).

In general, later studies should be considered as superseding early work so long as the previous details are carried forward and applied correctly.

A.2 UK level

Motyka and Brampton (1993) provided a review of coastal cells for England and Wales, with HR Wallingford (1997) offering equivalent information for Scotland. This information is applicable to the immediate coastline, but does not support any description for the offshore influences or extend into estuaries.

The Southern North Sea Sediment Transport Study (ABP Research and Consultancy 2000, HR Wallingford et al. 2002) was designed to provide the broad appreciation and detailed understanding of sediment transport along the eastern coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent on the south side of the Thames Estuary. The study was commissioned by a group of 9 local authorities, together with the Environment Agency, English Nature and the dredging industry. The study's main objectives were to:

- identify sediment sources, transport pathways, volumes of sediment transport and areas of deposition, across the complete range of particle sizes and temporal scales
- identify the location, size, variability and evidence of offshore features, and their influence on and interaction with waves and tidal current climates
- provide information that is required for the updating of SMPs, and which enables a more informed assessment to be made of the influence of offshore dredging on the eastern coast of England

The UK FUTURECOAST project (Halcrow 2002), which was commissioned by Defra, sought to:

- conceptualise the factors affecting coastal change
- provide predictions of coastal evolutionary tendencies over the next 100 years

An important objective was to allow contemporary coastal processes and past, present and future management decisions to be placed within a longer term and wider scale framework that provided a vision for the coast and a scientific basis for considering the 'direction' for sustainable strategic management response.

Through the government's Offshore Energy Strategic Environmental Assessment (SEA) programme, a review was completed for sand transport pathways and sandbanks at the UK scale and for the 3 development strategic areas selected for Round 2 offshore wind developments – Outer Wash, Outer Thames and North West. The findings of this research are reported in Kenyon and Cooper (2005), with the UK wide description of offshore sediment pathways offering a complimentary view to the coastal cells published by Motyka and Brampton (1993).

A.3 East Coast

A.3.1 Coastal Cell 1

The Cell 1 Sediment Transport Study (Royal Haskoning 2014) was commissioned by Scarborough Borough Council on behalf of all public authorities and other organisations with coastal interests within Coastal Cell 1. This frontage covers the coastline between St Abb's Head in Scotland and Flamborough Head in the East Riding of Yorkshire.

The study's objective was to improve understanding of governing sediment transport mechanisms and pathways across Coastal Cell 1 to help improve future coastal management decision-making. Although potential drift rates were considered, there is no specific definition of a sediment budget.

A.3.2 Coastal Cell 2, 3 to 4a

The Southern North Sea Sediment Transport Study was commissioned by local authorities to help improve the understanding of the southern North Sea sediment transport system and the linkages with the coastline between Flamborough Head and the River Thames. There was development of sediment pathways and identification of sources and sinks, but no specific definition of a sediment budget.

The Humber MAREA (2012)[5] was the last of 4 similar regional studies which included a consideration of seabed morphology, physical processes and sediment transport as part of a regional environmental assessment (REA) to help the consideration of cumulative impacts of marine aggregate extraction for subsequent EIA level assessment in support of marine licensing. The Humber REA covered the area between Flamborough Head and Cromer, and redefined the description of some sediment transport pathways.

A.3.3 Humber Estuary

Work undertaken for the Environment Agency for the Humber Estuary SMP (an area not completely covered by Cell 3b to 2c) developed a preliminary net sediment budget (Townend and Whitehead 2003). This suggested a finely balanced budget based on very small net residual exchanges compared with gross exchanges through the estuary mouth per tide. The work also highlighted that the sources and sinks are considerably smaller than the resident suspended load, which remains high across the estuary.

A.3.4 Coastal Cell 3b to 3c

A further regional examination of sediment pathways, covering parts of the coastline within Cell 3b to 3c was published for The Crown Estate in 2008 (Cooper et al. 2008).

A.3.5 Coastal Cell 3d to 4a

The Thames MAREA (2010)[5] was one of 4 similar regional studies which included a consideration of seabed morphology, physical processes and sediment transport as part of an REA to help the consideration of cumulative impacts of marine aggregate extraction for subsequent EIA level assessment in support of marine licensing. The Thames REA covered the outer Thames between Clacton-on Sea to North Foreland, and redefined the description of some sediment transport pathways.

A.3.6 Thames Estuary

For the Thames Estuary itself (an area not covered by Cell 3d to 4a), the Port of London Authority offers information for a sediment budget[6] based on work by the Institute of Estuarine and Coastal Studies in 1993. This budget suggests that the estuary exists in a balance between sediment deposition and erosion over a number of tidal cycles or seasons, and there is neither significant loss nor gain of sediment from the estuary. However, this balance could be affected by a variety of new anthropogenic factors or natural variations, such as accelerated sea level rise.

A.4 South Coast

A.4.1 Coastal Cell 4b to 4c

The South East Coastal Group has reported a comprehensive examination of shoreline change as a programme of regional shingle sediment budget reports extending from Herne Bay to Brighton Marina (EKEP 2013). The work examined volumetric change at 50m increments using LiDAR data for the period 2003 to 2012 (the frequency of

[5] www.marine-aggregate-rea.info
[6] www.pla.co.uk/Environment/Sediment-Budget

surveys was greater than one year in most cases and occasionally at different years along this frontage) and also considered other historic data back to 1890.

An important assumption in the analysis was that the basis of all volume change followed the well described direction of net littoral drift but also ignored the potential for any drift reversals influencing the survey data. A sequence of local sediment budgets was produced at the scale of management units which was then upscaled to summaries a regional budget. EKEP (2013) provides a useful summary of assumptions and limitations in the derivation of the sediment budget.

A.4.2 Coastal Cell 4c

The East Channel MAREA (2003)[7] was the first of 4 similar regional studies which included a consideration of seabed morphology, physical processes and sediment transport as part of an REA to help the consideration of cumulative impacts of marine aggregate extraction for subsequent EIA level assessment in support of marine licensing. The East Channel REA covers the area from Dover to Beachy Head and referred to previous work (Grochowski et al. 1993) to describe sediment transport pathways.

A.4.3 Coastal Cell 4d to 6b

This area along the South Coast includes the South Downs Coastal Group, the SCOPAC region, and the Lyme Bay and South Devon Coastal Group.

This region has recently received an update to the original sediment transport study completed in 2004 for SCOPAC. The study area spans the coastline between Start Point in Devon and Beachy Head in East Sussex. It is broken down into 27 sediment sub-cell units, each provided with a map of sediment pathways at the coast and exchanges with the adjacent estuaries and offshore locations, as applicable. This map illustrates sediment type, direction, volume, transport mechanism and reliability of information. The arrows on the map can be interrogated to provide supporting information. The revision issued in 2017 takes into account data and information up to 2012.

The area is also supported by the South Coast REA (2010).[7] One of 4 similar regional studies which included a consideration of seabed morphology, physical processes and sediment transport as part of an REA to help the consideration of cumulative impacts of marine aggregate extraction for subsequent EIA level assessment in support of marine licensing. The South Coast REA extends from Gilkicker Point to Durlston Head, but excludes the inner part of the Solent. No sediment pathways were established in this work.

A.4.4 Coastal Cell 6c to 6e

There are no known regional sediment studies for this cell.

A.5 West Coast

A.5.1 Coastal Cell 7a to 7b

There are no known regional sediment studies for this cell.

[7] www.marine-aggregate-rea.info

A.5.2 Coastal Cell 7c to 8c

This area covers the larger part of the Bristol Channel and Severn Estuary, and is an area studied in 1989 for the Severn tidal barrage and again in 2010 for the Severn Tidal Power SEA options. In addition, the Welsh Assembly Government commissioned the Bristol Channel Marine Aggregates Resources and Constraints project in 2000 to help support its consideration of marine aggregate dredging. The combination of all this work included examination of sediment sources and pathways, and the development of a broad sediment budget for the Severn Estuary.

In addition, Cell 8b to 8c was the subject of a coastline response study from Lavernock Point to Worms Head in 1993 (Bullen 1993). This work also established sediment pathways as well as considering links between linear sandbanks and the adjacent beaches.

A.5.3 Severn Estuary

As part of a set of supporting studies for the Severn Tidal Power SEA, the hydraulics and geomorphology topic published a sediment budget for the Severn Estuary (DECC 2010). This was largely based on previous work but with a re-examination of the contribution from intertidal and rivers contributions, as well as suspended sediment concentrations – all drawing on more recent data. Large uncertainties remained in the updated budget with a balance with the Bristol Channel exchange depending on the reliability of short-term LiDAR data redefining the behaviour of the intertidal losses and gains with an implication of changing the estuary from a net exporter to a net importer of fine sediments.

A.5.4 Coastal Cell 8d to 10b

There is no known regional sediment study for this cell.

A.5.5 Coastal Cell 11

The whole of Cell 11 is the subject of a bespoke sediment transport study commissioned by the North West & North Wales Coastal Group to inform coastal management in the region. A report on the Cell Eleven Tidal and Sediment Transport Study (CETaSS) was published in 2008 (Halcrow 2008).

A conceptual understanding was developed from this work and recommendations provided to develop a uniform cell wide approach to the definition of potential alongshore transport rates across the open sections of coastal frontage to inform sediment budgets for the region. This further work was based on wave data for the period 1989 to 2006 (Halcrow 2010). Modelled transport rates are reported at 141 locations on the open coast around the perimeter of the study area. They provide updrift and downdrift transport rates, net and standard deviation values as well as a breakdown between winter and summer average rates in the period. The comparison of the modelled transport rates to any monitoring of changes in beach profiles is not given.

Appendix B: Sources of data

What data are needed?	Where do I get the data?	Primary or secondary data	How used in SBA?[1]
Coastal topography	National Network of Regional Monitoring Programmes for shallower nearshore data (www.coastalmonitoring.org) UK Hydrographic Office for deeper offshore areas suitable for navigation of commercial craft (www.gov.uk/guidance/inspire-portal-and-medin-bathymetry-data-archive-centre)	Primary	Change in topography/ bathymetry used to help derive volume of change associated with erosion/ accretion, as well as the potential source and sink terms Q_{source} Q_{sink} ΔV
Beach management activities	The regional monitoring programmes maintain records of beach management activities (volumes).	Primary	Volumes of material involved with beach recharge (that is, positive contribution) P
Cliff erosion	For systems that offer an input of sediment from cliff erosion, past cliff recession rates can be deduced from a series of old topographic maps. iCOASST has recently made the open source version of SCAPE+ (Soft Cliff And Platform Erosion) freely available. This can help to determine and predict the future contribution of cliff material into a system (www.channelcoast.org/iCOASST/SCAPE/).	Primary *(maps/ cliff line surveys)* Secondary *(modelling outputs)*	Change in cliffline used to help derive potential source term Q_{source}

What data are needed?	Where do I get the data?	Primary or secondary data	How used in SBA?[1]
River flow	The Centre for Ecology and Hydrology is the primary data archive centre for gauged river flows in the UK (http://nrfa.ceh.ac.uk). Care should be taken when referring to river gauges that are high up in catchments and which do not account for any additional contributions from the lower catchment.	Primary	Flow information may be combined with data on suspended sediment concentrations to help derive potential source term Q_{source}
Sediment concentrations in rivers	Sediment concentration information is likely to be limited in river systems and to vary greatly in magnitude and sediment type under spate (storm) conditions as sediment is washed from the catchment.	Primary	
Offshore[2]	It is likely that all offshore data will have to be derived through numerical modelling of some form calibrated with flow, water level, bedload and depth-averaged suspended sediment data.	Secondary	–
Offshore surface suspended sediment (SSC)	For systems with high levels of suspended sediment in the main water body (as may be common in many large UK estuaries) then suspended sediment concentrations will be required to characterise the sediment load. Additional deduction of surface suspended particulate matter and extent is also possible from satellite imagery as described in (Silva et al. 2016). These data are most valid in open water and at concentrations less than 25g/m³. Estuaries and areas with higher concentrations are likely to be out	Primary	Used to help inform volume of sediment in water column. SSC information may therefore need to be combined with modelling output to calculate volume. Q_{source} Q_{sink}

What data are needed?	Where do I get the data?	Primary or secondary data	How used in SBA?[1]
	of range of this analysis.		
Maintenance dredge records	For systems with licensed maintenance dredging (that is, to maintain access through approach channels and at harbour berths) and disposal sites, the associated data can be obtained from the local port(s) or with reference to annual FEPA disposal at sea values compiled for Defra for England and Wales.	Primary	Volumes of material involved with dredging (that is, negative contribution) *R*
Aggregate extraction	For systems with licensed mineral extraction sites of marine aggregates, annualised quantities of removal and areas involved are published on an annual basis by The Crown Estate (www.thecrownestate.co.uk/energy-minerals-and-infrastructure/downloads/marine-aggregate-downloads/) and the British Marine Aggregate Producers Association (www.bmapa.org/issues/area_dredged.php).	Primary	

Notes: [1] Source/store/sink terms provided in Equation 4.2 of the main text (Rosati and Kraus 1999) are also given.
[2] The term ‘offshore’ is not explicitly defined but will instead vary between projects.

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